Linear Collider Physics at lower Energies

Klaus Mönig

DESY-Zeuthen

- Introduction
- The GigaZ scenario
- Electroweak physics
- B-physics
- Other ideas
- Detector issues
- Conclusions

Physics at $\sqrt{s} \sim m_{\mathrm{Z}}(-200\,\mathrm{GeV})$ has proven to be very fruitful in the past:

- Electroweak precision tests can probe physics at high scales and can test the consistency of the favourite model at the loop level.

- The Z-pole is a rich source for some particles (B,D,τ) with distinct advantages to lower energy machines.

It is therefore worth to study what we can learn from a much increased integrated luminosity in the light of the competition from TEVATRON run II, LHC and the B-factories

This talk tries to point out the possibilities of a linear collider and is necessarily on the optimistic side. It is meant to motivate further work on the subject.

The GigaZ scenario

The talk is based on the following assumptions:

- $> 10^9$ recorded Z-decays
  - ➠ $\sim 50 - 100$ days at $\mathcal{L} = 5 \cdot 10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
  - ➠ a Z-rate of $\sim 100 - 200$Hz
- high polarisation of the electron beam ($> 80\%$)
- very high precision on polarimetry ($\mathcal{O}(0.1\% - 0.5\%)$) and/or positron polarisation ($> 20\%$)

GigaZ running modes

- NLC scheme
  - e^--beam independent positron source
  - can start early with GigaZ and upgrade to high energy later
- TESLA scheme
  - positron source using high energy e^- beam
  - use one part of the machine for 45 GeV beam and the other part for positron production
  - start with physics at high energy and come back to the Z later

Which luminosity can be reached?

	NLC		TESLA
	norm	low δ_B	
$\mathcal{L}\,(10^{33})$	4.1	2	5
$\delta_B\,(\%)$	0.16	0.05	0.1
$\Delta\mathcal{P}_{\rm IP}\,(\%)^*$	0.07	0.02	0.1

(* for spent beam, for colliding particles $\sim$ factor four smaller)

Which statistics can be reached?

- Total cross section $\sigma \approx \sigma_u(1 + \mathcal{P}_{\rm e^+}\mathcal{P}_{\rm e^-})$
  ($\sigma_u \approx 30$nb)
- With $\mathcal{L} = 5 \cdot 10^{33}{\rm cm}^{-2}{\rm s}^{-1}$:
  - $\sim$ 50 days for 10^9 Zs with $\mathcal{P}_{\rm e^-}/\mathcal{P}_{\rm e^+} = 0.8/0.6$
  - $\sim$ 80 days for 10^9 Zs with $\mathcal{P}_{\rm e^+} = 0$

$\Rightarrow$ 10^9 Zs should be possible within the normal LC running budget

$\Rightarrow$ 10^{10} Zs can be produced with a dedicated facility in 3–5 years (150 days/year)

Interesting quantities:

- normalisation of axial-vector coupling of $Z \to \ell\ell$: $\Delta\rho_\ell$
- effective weak mixing angle from ratio of vector to axial vector coupling of $Z \to \ell\ell$: $\sin^2\theta^\ell_{\mathrm{eff}}$
- mass of the W: m_{W}
- strong coupling constant from the Z hadronic decay rate: $\alpha_s(m^2_{\mathrm{Z}})$
- vertex correction to Zbb vertex: $R_{\mathrm{b}}, \mathcal{A}_{\mathrm{b}}$

$\Delta\rho_\ell$, $\alpha_s(m^2_{\mathrm{Z}})$

Minimally correlated observables:

	LEP precision
m_{Z}	$0.2 \cdot 10^{-4}$
Γ_{Z}	$0.9 \cdot 10^{-3}$
$\sigma_0^{\mathrm{had}} = \frac{12\pi}{m^2_{\mathrm{Z}}}\frac{\Gamma_e\Gamma_{\mathrm{had}}}{\Gamma^2_Z}$	$0.9 \cdot 10^{-3}$
$R_\ell = \frac{\Gamma_{\mathrm{had}}}{\Gamma_l}$	$1.2 \cdot 10^{-3}$

$\Rightarrow$ Need to scan

$\Rightarrow$ Need absolute cross sections

Assumptions:

- relative beam energy error around Z-pole: 10^{-5}
  $\Rightarrow \Delta\Gamma_Z/\Gamma_Z = 0.4 \cdot 10^{-3}$
  (Need to understand the beam energy measurement and the systematics due to beamstrahlung and beamspread)
- selection efficiency for μs, τs, hadrons (and exp error on $\mathcal{L}$) improved by a factor three relative to the best LEP experiment
  $\Rightarrow \Delta R_\ell/R_\ell = 0.3 \cdot 10^{-3}$
- theoretical error on luminosity stays at 0.05%
  $\Rightarrow \Delta\sigma_0^{\mathrm{had}}/\sigma_0^{\mathrm{had}} = 0.6 \cdot 10^{-3}$
  (again if beamspread/-strahlung understood)

Improvement on lineshape related quantities:

	LEP	GigaZ
m_Z	91.1874 ± 0.0021 GeV	± 0.0021 GeV
$\alpha_s(m_Z^2)$	0.1183 ± 0.0027	± 0.0009
$\Delta\rho$	$(0.55 \pm 0.10) \cdot 10^{-2}$	$\pm 0.05 \cdot 10^{-2}$
N_ν	2.984 ± 0.008	± 0.004

$\sin^2\theta^\ell_{\rm eff}$:

Most sensitive observable is $A_{\rm LR}$, so only this is discussed

$$A_{\rm LR} = \frac{1}{\mathcal{P}}\frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = \mathcal{A}_{\rm e} = \frac{2v_e a_e}{v_e^2 + a_e^2}$$

$$v_e/a_e = 1 - 4\sin^2\theta^\ell_{\rm eff}$$

independent of the final state

Statistical error with 10^9 Zs: $\Delta A_{\rm LR} = 4 \cdot 10^{-5}$

(for $\mathcal{P}_{\rm e^-} = 80\%$, $\mathcal{P}_{\rm e^+} = 0$)

Crucial ingredient: polarisation measurement

Error from polarisation: $\Delta A_{\rm LR}/A_{\rm LR} = \Delta\mathcal{P}/\mathcal{P}$

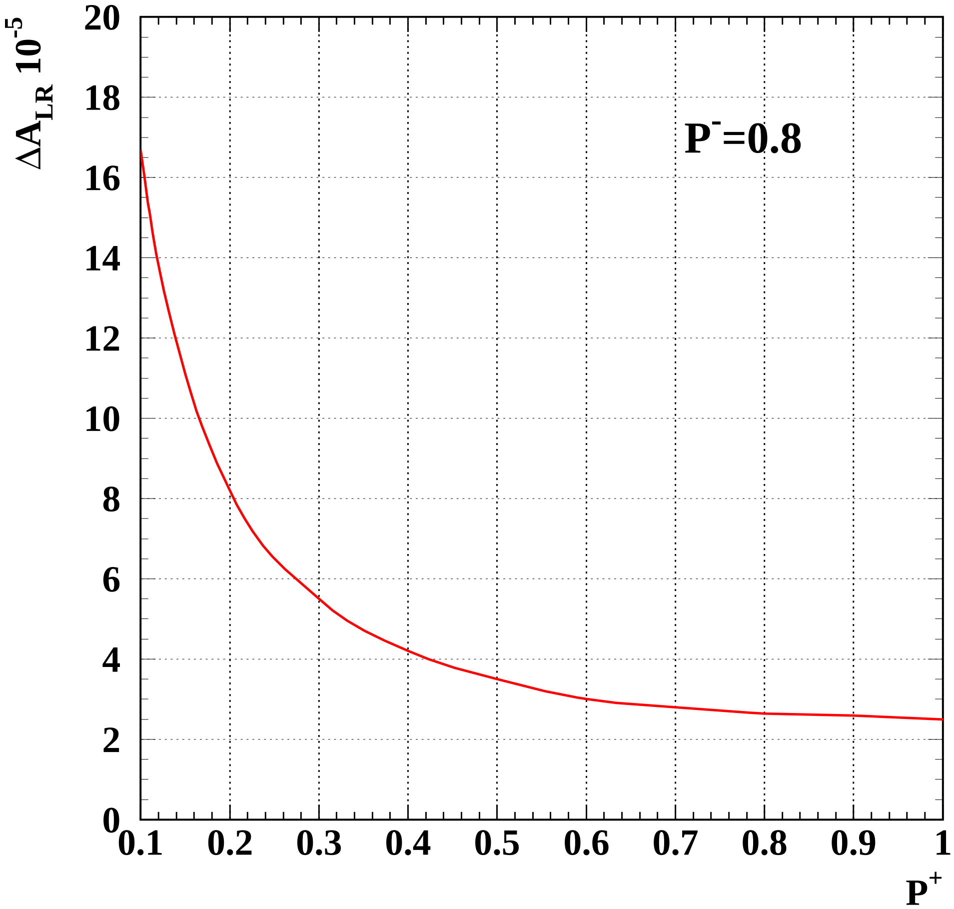
- only electron polarisation with $\Delta\mathcal{P}/\mathcal{P} = 0.5\%$ $\Rightarrow \Delta A_{\rm LR} = 8 \cdot 10^{-4}$
  (Still factor three to SLD, but few million Zs are sufficient)
- with positron polarisation $\mathcal{P}_{\rm eff} = \frac{\mathcal{P}_{\rm e^+}+\mathcal{P}_{\rm e^-}}{1+\mathcal{P}_{\rm e^+}\mathcal{P}_{\rm e^-}}$
  $\Rightarrow$ gain a factor four for $\mathcal{P}_{\rm e^-}/\mathcal{P}_{\rm e^+} = 80\%/60\%$ due to error propagation
  (even when error is 100% correlated between the polarimeters the gain is a factor three)

$$\sigma = \sigma_u \left[1 - \mathcal{P}_{e^+}\mathcal{P}_{e^-} + A_{LR}(\mathcal{P}_{e^+} - \mathcal{P}_{e^-})\right]$$

$$A_{LR} = \sqrt{\frac{(\sigma_{++} + \sigma_{-+} - \sigma_{+-} - \sigma_{--})(-\sigma_{++} + \sigma_{-+} - \sigma_{+-} + \sigma_{--})}{(\sigma_{++} + \sigma_{-+} + \sigma_{+-} + \sigma_{--})(-\sigma_{++} + \sigma_{-+} + \sigma_{+-} - \sigma_{--})}}$$

can measure A_{LR} independent from polarimeters with very small loss in precision and only 10% of the luminosity on the small cross sections

ΔA_{LR} as a function of the e^+ polarisation



For 10^9 Zs already 20% positron polarisation is better than a 0.1% polarimeter!

Crucial problem for Blondel scheme: Difference of absolute values of helicity states.

For $\mathcal{P} = \pm|\mathcal{P}| + \delta\mathcal{P}$: $\mathrm{dA_{LR}}/\mathrm{d}\delta\mathcal{P} = 0.5$ for e^- and e^+ separately

$\Rightarrow$ understand polarisation difference to $< 10^{-4}$

Many effects can be treated with a polarimeter with several channels with different analysing power

$\rightarrow$ control of the laser-polarisation difference

$\rightarrow$ control of asymmetric backgrounds

Further issue: polarisation correlation effects (e.g. correlated time dependencies, depolarisation effects in the interaction region, transverse dispersion effects)

Order of magnitude estimate:

- change $\Delta\mathcal{P}/\mathcal{P}$ by $\pm 1\%$ for e^+ and e^- simultaneously for half of the luminosity

$\Rightarrow \Delta A_{\mathrm{LR}} = 0.7 \cdot 10^{-5}$

- Effect goes quadratic with $\Delta\mathcal{P}/\mathcal{P}$
- Seems not to be a big problem

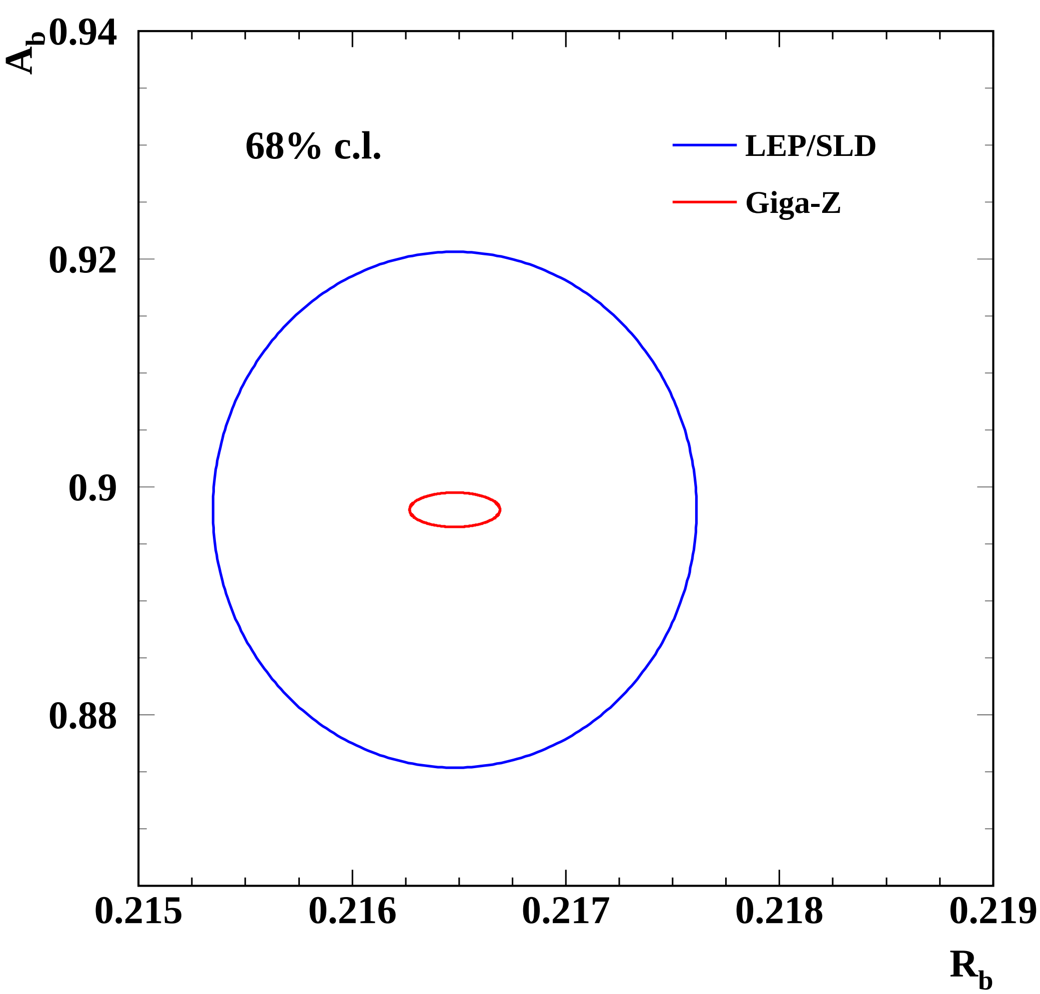
Other systematics

- Beam energy: $\mathrm{dA_{LR}/d\sqrt{s}} = 2 \cdot 10^{-2}/\,\mathrm{GeV}$ from $\gamma - Z$-interference
  $\Rightarrow$ need $\Delta\sqrt{s} \sim 1\,\mathrm{MeV}$ relative to m_{Z}
- Beamstrahlung: $\Delta A_{\mathrm{LR}} = 9 \cdot 10^{-4}$ (TESLA)
  $\Rightarrow$ need to know beamstrahlung to a few %
  However if beamstrahlung is the same in m_{Z}-scan and A_{LR}-running corrections are automatic
- (Energy spread is not relevant for A_{LR} since slope is linear)
- Other systematics should be small

In total $\Delta A_{\mathrm{LR}} = 10^{-4} \Rightarrow \Delta \sin^2\theta^{\ell}_{\mathrm{eff}} = 0.000013$ seems a realistic estimate
Factor 13 to LEP/SLD

b-quark observables

- R_b:
  - factor five to LEP/SLD due to better b-tagging and higher statistics
- $\mathcal{A}_b$:
  - factor 15 to LEP/SLD due to higher statistics, beam polarisation and b-tagging
  - If the slight discrepancy currently seen at LEP/SLD is real it cannot escape GigaZ



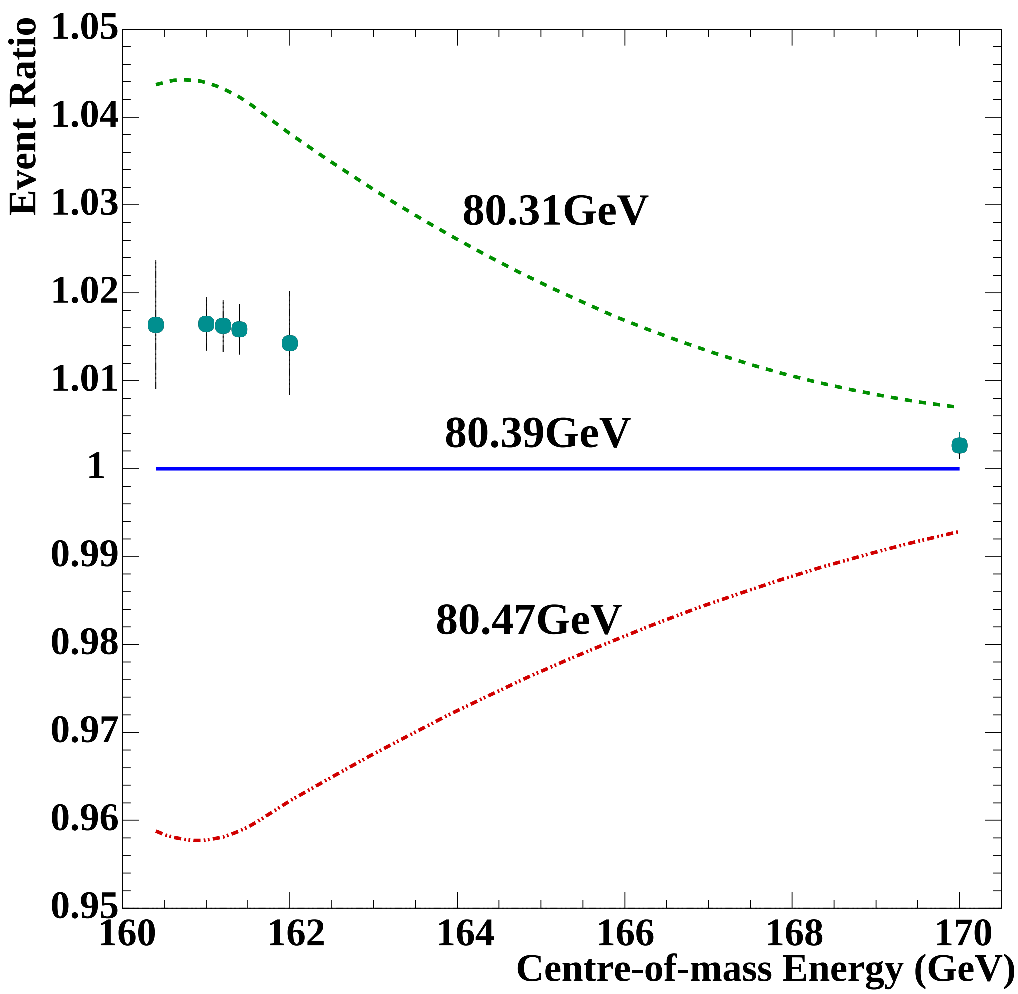
Threshold scan:

- Near threshold W-pair production is dominated by neutrino t-channel exchange

$\Rightarrow$ β-suppression gives high sensitivity to m_{W}

$\Rightarrow$ no (unknown) triple gauge couplings involved

- A six point scan around $\sqrt{s} = 161\,\mathrm{GeV}$ has been simulated with $\mathcal{L} = 100\,\mathrm{fb}^{-1}$ (one year!!!)



- Efficiencies/purities assumed as at LEP
- Polarisations used to measure background/ enhance signal
  - need $\Delta\mathcal{P}/\mathcal{P} < 0.25\%$
  - can use Blondel scheme on rad. ret. events if positron polarisation is available
  - $A_{\mathrm{LR}}^{f\bar{f}}(160)\,\mathrm{GeV}$ large, rapidly changing with $\sqrt{s}$ and different for up- and down-type quarks
    $\Rightarrow$ need to understand left-right asymmetry for selected background very well

➨ $\Delta m_{\mathrm{W}} = 6\,\mathrm{MeV}$ possible with 0.25% error on luminosity and efficiencies

- error increases only to 7 MeV if efficiencies are fitted

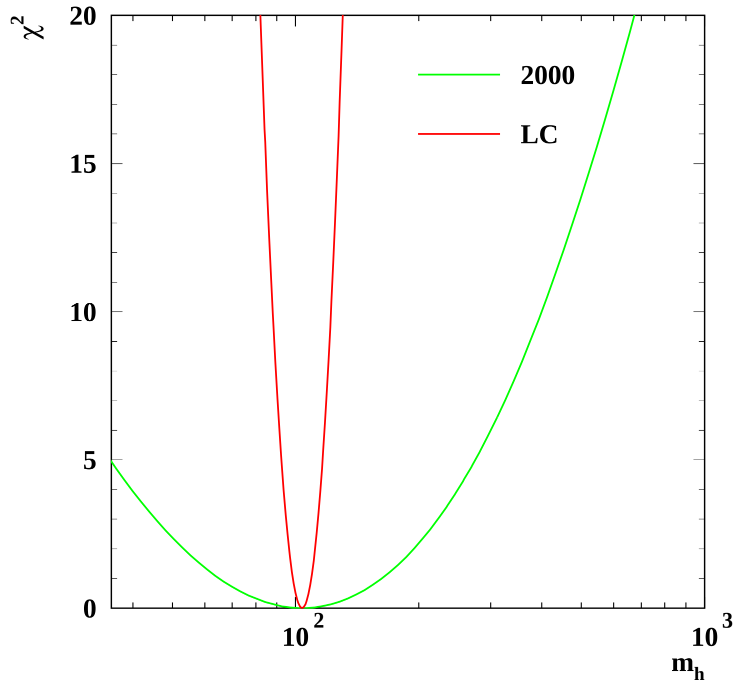
➨ Factor 2-3 better than LHC

Parametric errors

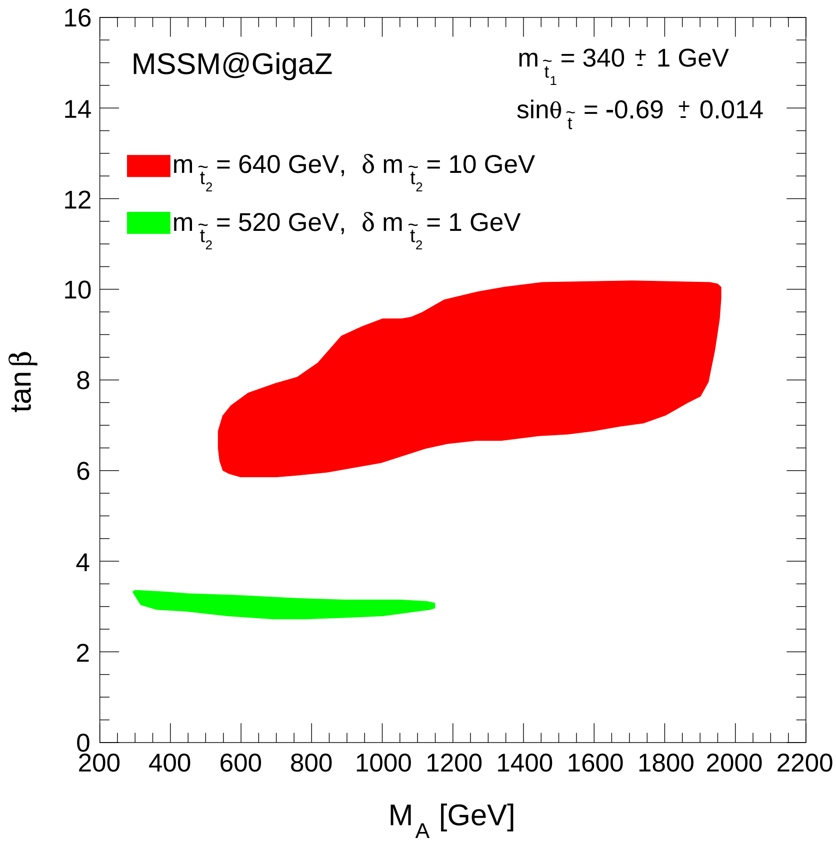
- largest effect: Running of α
  - Using data only (including the latest BES results): $\Delta\sin^2\theta^\ell_{\mathrm{eff}} = 0.00014$, $\Delta m_{\mathrm{W}} = 7\,\mathrm{MeV}$
  - $\sim$ factor three improvement using perturbative QCD at low energy
  - with $\sigma(\mathrm{e^+e^-}\to\mathrm{had})$ below the Υ to 1% $\Delta\sin^2\theta^\ell_{\mathrm{eff}} = 0.000017$, $\Delta m_{\mathrm{W}} < 1\,\mathrm{MeV}$
- $2\,\mathrm{MeV}$ error on m_{Z} gives $\Delta\sin^2\theta^\ell_{\mathrm{eff}} = 0.000014$, $\Delta m_{\mathrm{W}} = 1\,\mathrm{MeV}$ (if W-mass calibrated to m_{Z})
- $\Delta m_{\mathrm{t}} = 1\,\mathrm{GeV}$ gives $\Delta\sin^2\theta^\ell_{\mathrm{eff}} = 0.00003$, $\Delta m_{\mathrm{W}} = 6\,\mathrm{MeV}$
  $\Rightarrow$ no problem with LC precision of m_{t} ($< 200\,\mathrm{MeV}$)

($\sin^2\theta^\ell_{\mathrm{eff}}$ is at its limit from $\Delta\alpha(m_{\mathrm{Z}})$ and Δm_{Z}!)

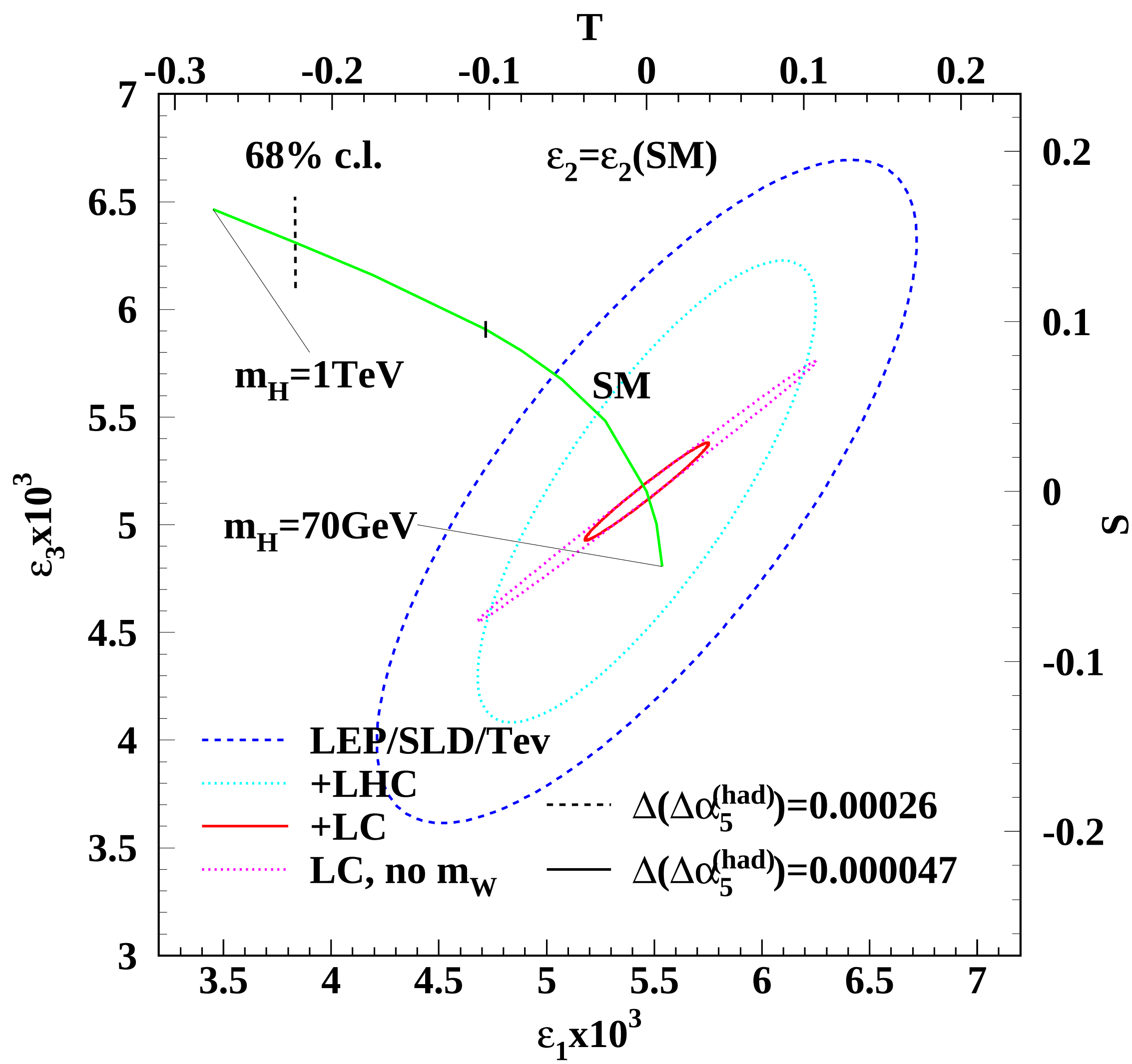
Within SM m_{H} can be predicted to 5% from precision data



Within the MSSM the data can be used to measure model parameters



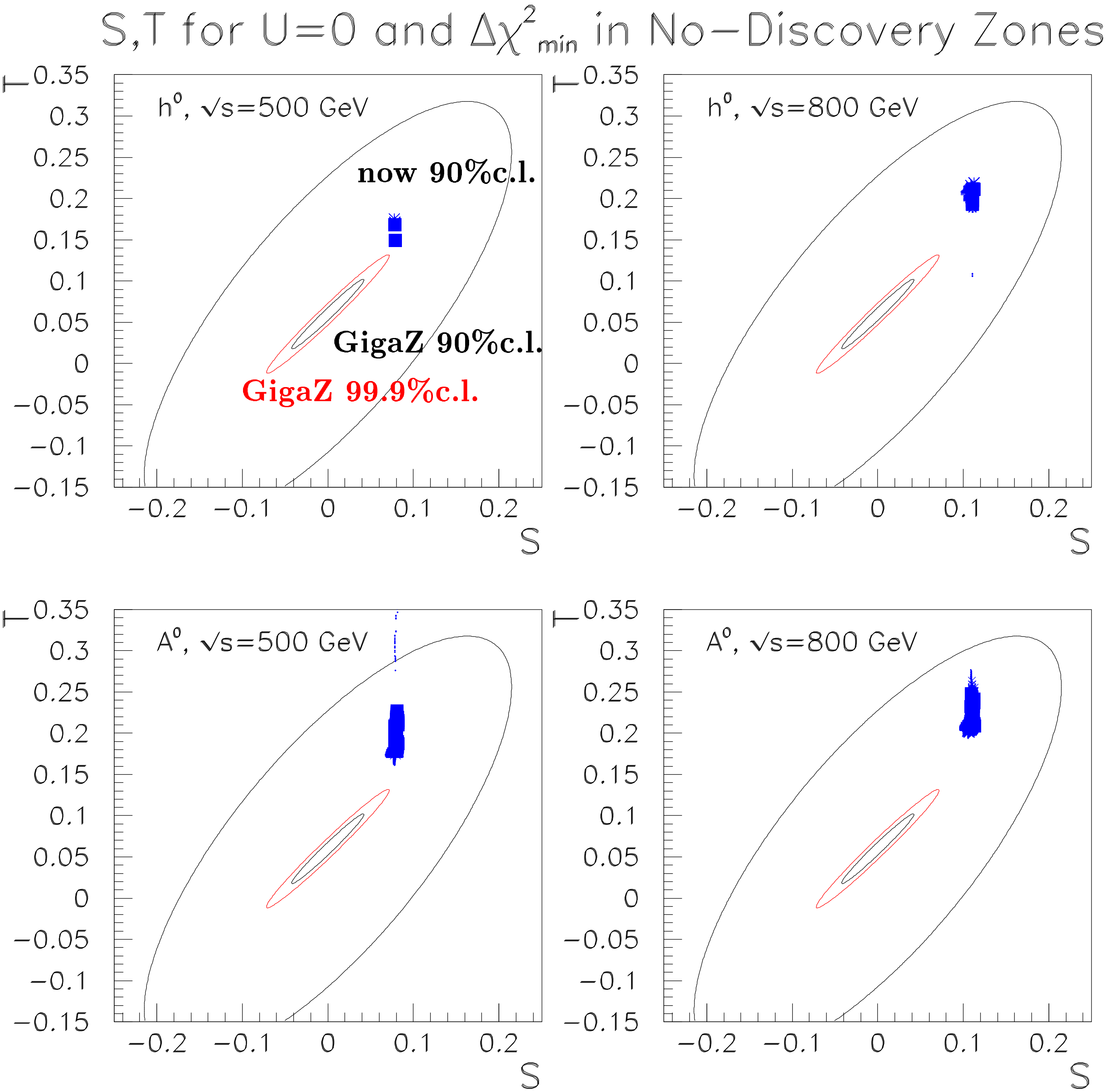
Model independent analysis (ε, ST parameters)



- dramatic improvement in m_{H} direction
- improvement perpendicular to m_{H} largely due to m_{W}
- significant Higgs constraint independent of ε_1 (T) possible

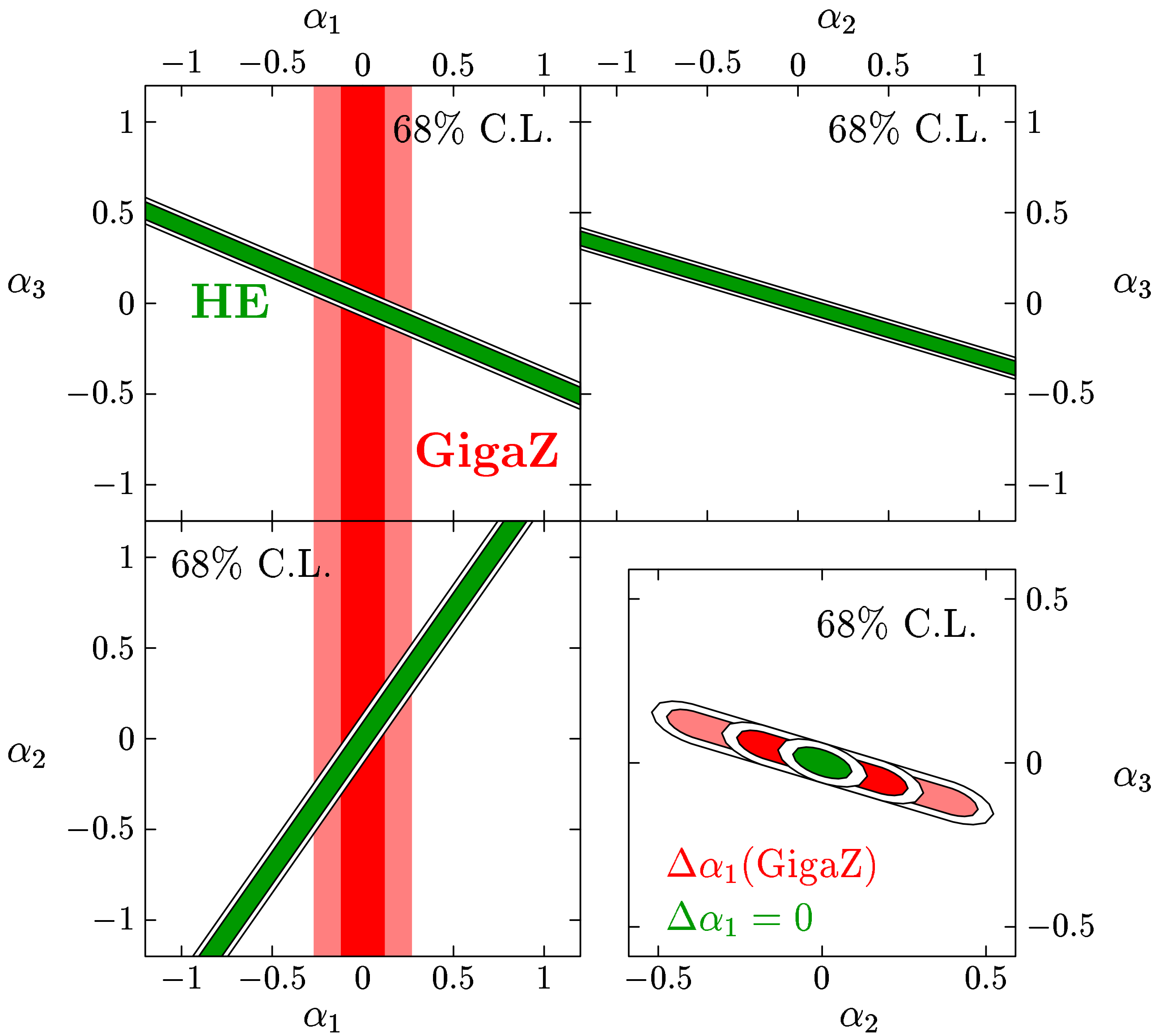
E.g. exclusion of a two Higgs doublet model with a light Higgs

(that cannot be excluded by direct searches)



For these types of exclusions m_{W} is important!

GigaZ also important for strong electroweak symmetry breaking:



Limits correspond to $\Lambda^* = \mathcal{O}(10\,\mathrm{TeV}) \gg 3\,\mathrm{TeV}$

Available statistics: $4 \cdot 10^8 - 4 \cdot 10^9$ B-hadrons for $10^9 - 10^{10}$ Zs

Comparison with e^+e^--B-factories

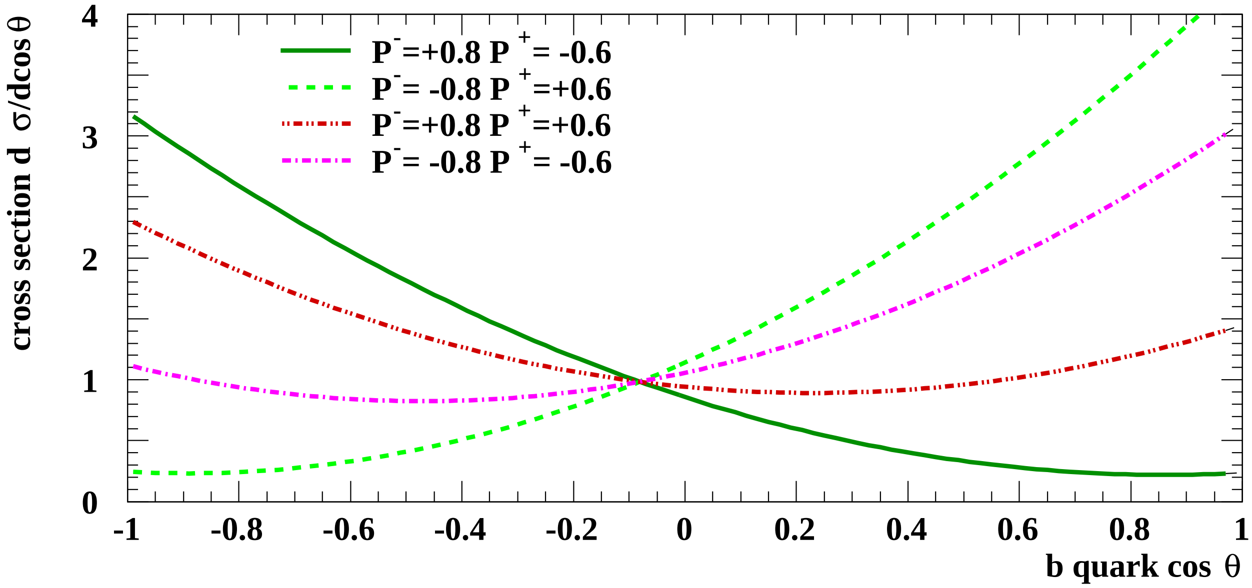
- comparable statistics
- large boost allows separation of the two Bs
- large boost gives much better decay length resolution
- also B_s and Λ_b produced
- large A_{FB} with polarised beams gives very good initial state charge tagging

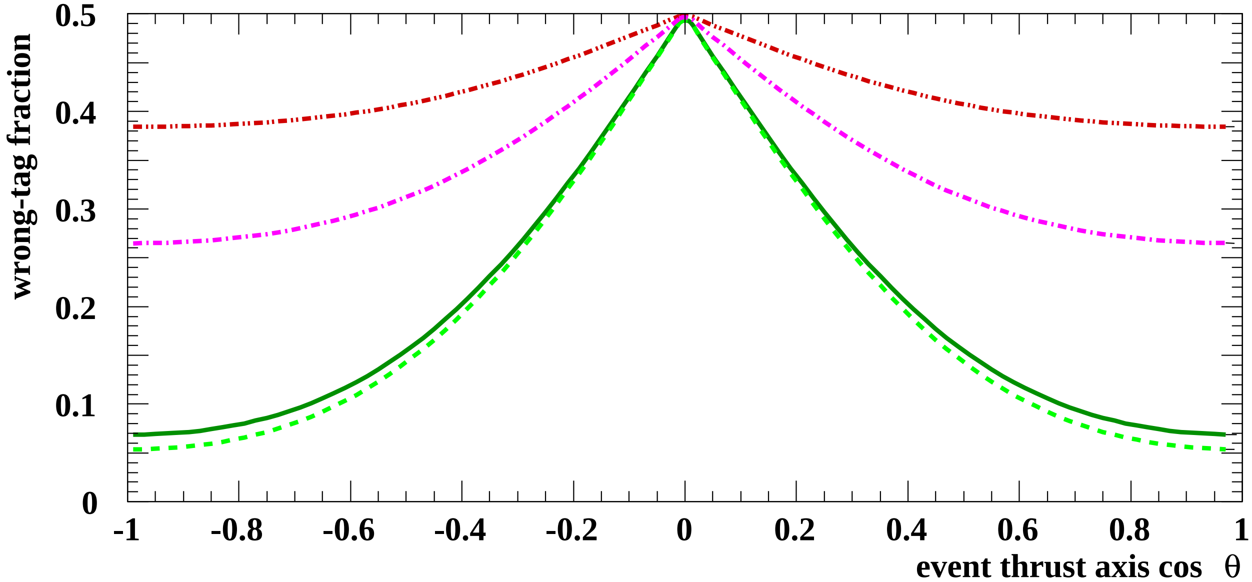
Comparison with LHC-b,BTeV

- much lower statistics
- however all Bs are triggered and can be reconstructed
- much cleaner environment

Up to now no GigaZ specific CP-studies, only repetition of B-factory/LHC-b/etc.

Primary flavour tagging from B-direction





$\epsilon D^2 \approx 0.6$ from B-direction only

Typical at other machines: $\epsilon D^2 \approx 0.1 - 0.25$

Other methods like vertex charge can strongly improve in central region, however no detailed studies yet.

Measure time dependent asymmetries

$$A(t) = \frac{N_{B^0}(t) - N_{\bar{B}^0}(t)}{N_{B^0}(t) + N_{\bar{B}^0}(t)} = a_c \cos \Delta m t + a_s \sin \Delta m t$$

mainly two examined decay modes

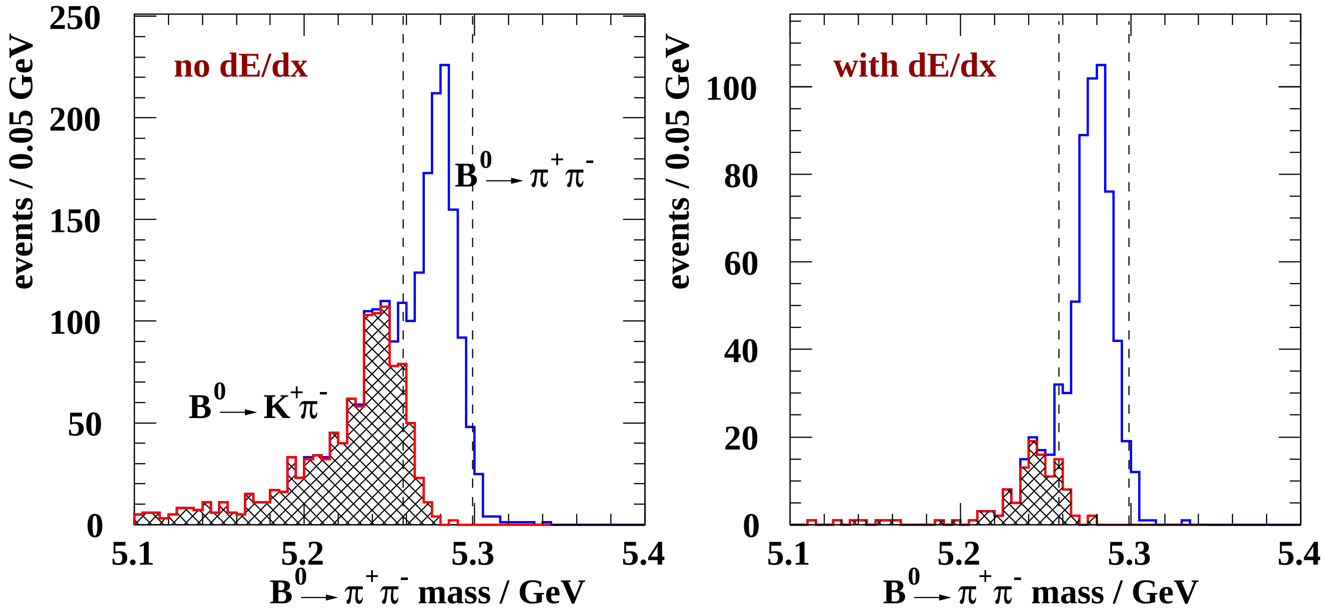
- $B^0 \to J/\Psi K_s^0$:
  - $a_s = -\sin 2\beta,\ a_c = 0$
- $B^0 \to \pi^+\pi^-$:
  - $a_s = -\sin 2\alpha,\ a_c = 0$ if penguin diagrams can be ignored
  - however a_s, a_c modified by penguin contributions, hard to calculate
  - can be disentangled by measuring branching ratios $B^0 \to \pi^+\pi^-$, $B^0 \to \pi^0\pi^0$, $B^+ \to \pi^+\pi^0$

Experimental analysis:

- identify initial state b-charge
- reconstruct decay mode
- measure eigentime to decay (easy in LC environment with fully reconstructed decays)

Final state identification:

- Missing particle ID can be replaced by excellent momentum resolution



(Without cut on B-decay angle) Results

	$\sin 2\beta$	"$\sin 2\alpha$"
BaBar/Belle	0.12	0.26
CDF	0.08	0.10
BTeV/year	0.03	0.02
ATLAS	0.02	0.14
LHC-b	0.01	0.05
GigaZ (10^9 Zs)	0.04	0.07

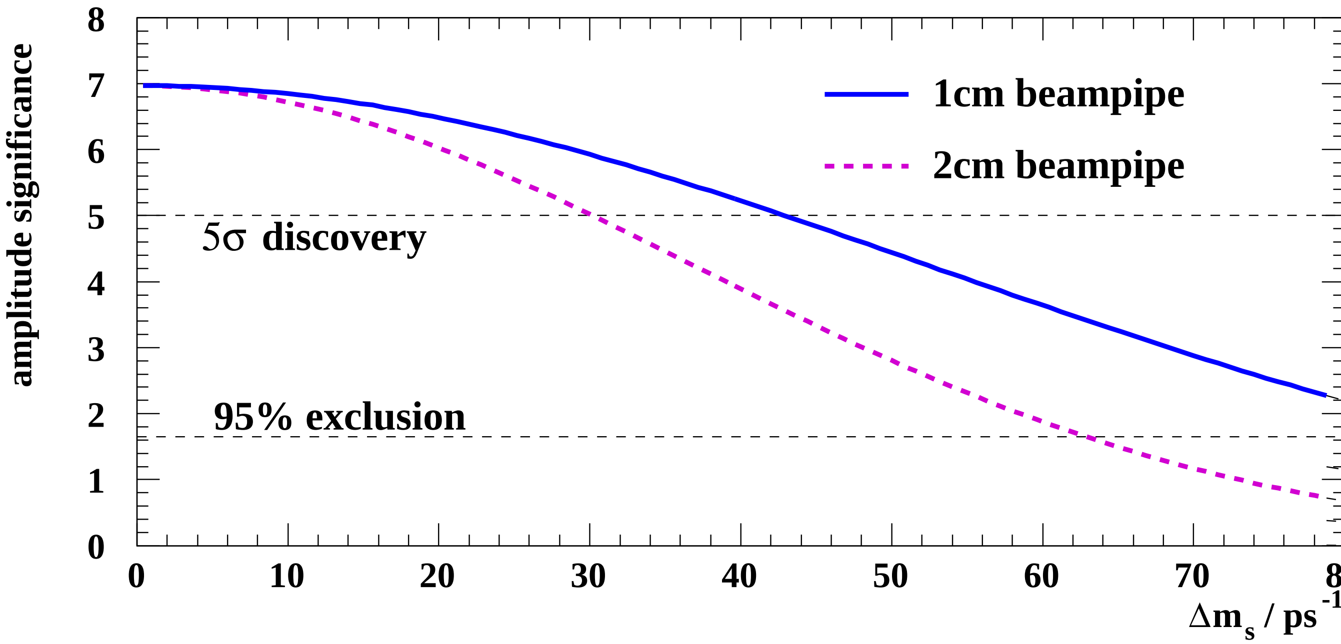
Interesting cross check with 10^9 Zs, with 10^{10} very competitive

Branching ratios $B^0 \to \pi^0\pi^0$, $B^+ \to \pi^+\pi^0$

- Competitive results to BaBar with 10^9 Zs

$B_s\overline{B}_s$-mixing

- "golden" mode: $B_s \to D_s\pi$, $D_s \to \phi\pi, KK$
- proper time res. dominated by vertex res.



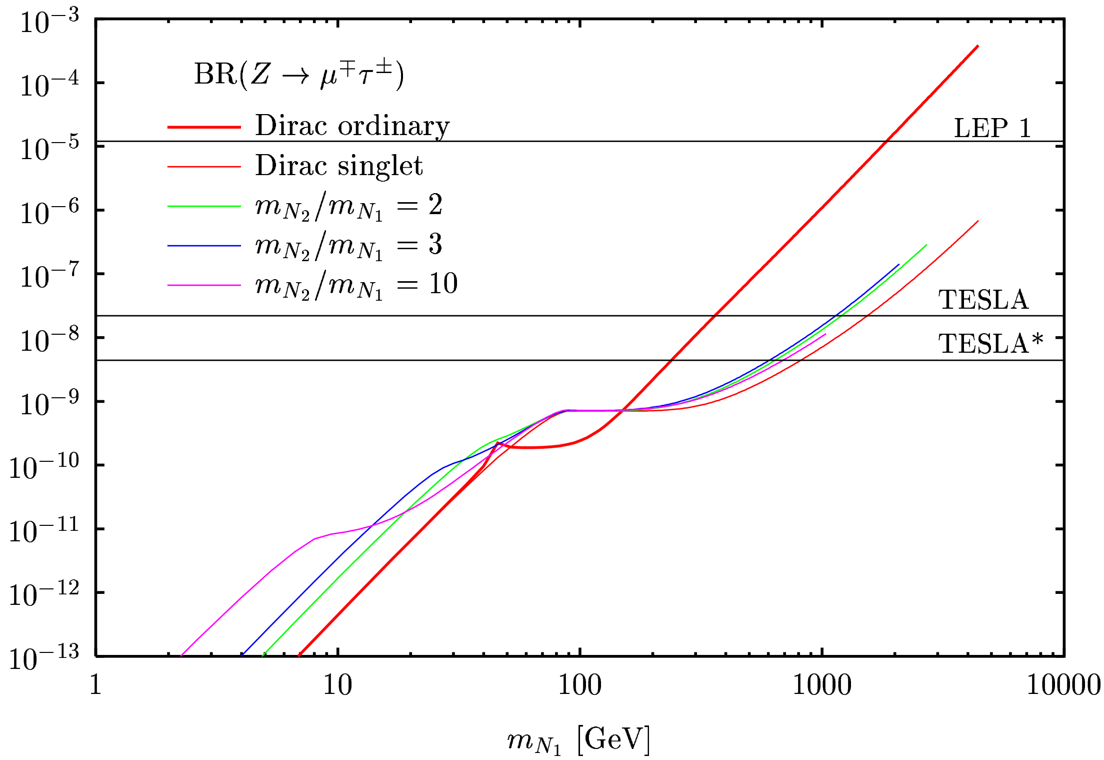
- $\Delta m_s \sim 40\text{ps}^{-1}$ possible
- resolution limit around $\Delta m_s \sim 80\text{ps}^{-1}$

And further

- Some rare b-decays might be accessible at GigaZ (e.g. $b \to s\nu\nu$)
- Tests of quark hadron duality (e.g. V_{cb} in B_s)

Rare Z decays

- with 10^9 Zs leptonic FCNC Z-decays like $Z \to e\tau, \mu\tau$ are visible on the 10^{-8} level
- e.g. some models with extra neutrinos predict signals on this level



- also some SUSY models predict measurable signals

Other possibly interesting fields

τ-physics, charm-physics, gluon jets, what else?

Considered running mode:

- $\mathcal{L} = 5 \cdot 10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1} \Rightarrow 200\mathrm{Z/s}$

Machine characteristics:

- NLC: 180 trains/s with 190 bunches/train and 1.4ns bunch spacing
- TESLA: 5 trains/s with 2800 bunches/train and 340ns bunch spacing

Number of Zs per bunch/train:

	NLC-train	TESLA-bunch
0 Zs	0.33	0.986
1 Z	0.37	$1.4 \cdot 10^{-2}$
2 Zs	0.20	$9.7 \cdot 10^{-5}$
$\geq$ 3 Zs	0.10	$4.5 \cdot 10^{-7}$

- Z counting should be possible at both machines
- Luminosity/bunch might be enlarged if more beamstrahlung is tolerated
  (Not for electroweak physics!)
- Need detailed studies how many Zs/train affect B-physics specific topics like b-/anti-b-tagging, energy flow etc.

Detector:

Electroweak physics:

- $\sin^2\theta^{\ell}_{\mathrm{eff}}$-measurement needs mainly Z-counting
- for partial widths need also good hermeticity and energy flow
- b-couplings require very good b-tagging

➨ the high energy detector is almost perfect

B-physics:

- π/K/p-separation certainly helps
- however specialised detectors (RICH) tend to compromise energy-flow and momentum resolution
- good mass resolution largely replaces particle-id
- dE/dx has to be available
- a high B-field separates particles in jets and improves dE/dx
- excellent vertexing also helps to separate Zs in one bunch/train

➨ also here the high-energy detector is very good

Preliminary conclusions

- With a modest effort a huge gain in the precision Z-observables is possible

- An improved m_{W} measurement is also possible if one spends a year for it

- These measurements allow stringent tests of the then-Standard-Model

- The CP-tests of BaBar/Belle/BTeV/LHC-b can be cross-checked with 10^9 Zs and possibly be improved with 10^{10} Zs

- Some new topics in B-physics, rare Z decays etc. can be studied

- By no means a present design should exclude the GigaZ option

- A facility with 10^{10} Zs looks interesting, but needs further study

Open questions for Snowmass

For electroweak physics (10^9 Zs):

- is e^+ polarisation possible, if yes, how much?
- how well can can we understand polarisation systematics?
- can we understand $\Delta\sqrt{s}/m_Z$ to 10^{-5}?
- how well can we understand beamstrahlung and beamspread?

For B-physics (10^{10} Zs):

- how many Zs/bunch,train can we accept?
- do we need additional particle id, what can we sacrifice for it?
- can we go closer to the beam with the vertex detector?